TECHNICAL REPORT

CONTOURED SKIN FRICTION TRANSDUCERS

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CAL No. AN-2403-Y-1

Sponsored By:

National Aeronautics and Space Administration/
Ames Research Center
Moffett Field, California 94035

Contract No. NAS 2-4053

August 1967

CORNELL AERONAUTICAL LABORATORY, INC.
OF CORNELL UNIVERSITY, BUFFALO, N. Y. 14221

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Ames Research Center
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Contract No. NAS 2-4033

Prepared by: R.C. MacArthur

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[illegible]

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ABSTRACT

A new type skin friction transducer intended for use in shock tunnels is described. The design is improved over previous transducers developed by CAL. A small, rugged and reliable amplifier is included within the 1/4" diameter by 5/8" thick transducer case. The active, i.e., skin friction, diaphragm may be replaced with a diaphragm of another contour to accommodate a different model shape. Acceleration compensation, an essential feature, is incorporated. Power gains of over one million make this device practically free of the troublesome cable noise usually experienced with similar devices when used at low skin friction levels.

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LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

l length in inches

w width in inches

t thickness in inches

d diameter in inches

r radius in inches

A area in inches^2

k dielectric constant

c capacitance in picofarads

C thermal capacity in BTU/lb.

p pressure in psi

τ skin friction in psi

$\dot{q}$ heat transfer rate in BTU/ft^2 sec

T temperature degrees fahrenheit

g_{31} piezoelectric constant in $\frac{\text{volt meters}}{\text{Newton}}$ (See footnote, p. 6)

Subscripts

b beam

d diaphragm

SECTION I INTRODUCTION

Cornell Aeronautical Laboratory (CAL) has been actively engaged in the development and use of short-duration aerodynamic test facilities and their instrumentation since 1950; shock tunnel operation has been on a scheduled routine basis for more than seven years. Almost all of the instrumentation used in this work has been developed at CAL. Until 1962, tests were limited to measurement of pressure, force, heat transfer and shock speed. During 1962, the use of skin friction gages was pioneered with good results. Reference 1 discusses the early experience in the application and utilization of these gages.

Since that time, improvements have been made and incorporated in the subsequent models. The porous diaphragm, on which a patent is now pending, is one of those improvements; a second, a 1/4" diameter design, uses the porous principle and also a reduced diameter for easier application to curved surfaces. Many skin friction transducers have been used in CAL programs on both internal and external curved surfaces.

During 1964, a program was started at this Laboratory to use field effect transistors (FET's) as low noise power amplifiers. They are small enough and otherwise suitable for installation inside test models close to the transducers, thus eliminating the loss in signal produced by the shunt capacitances inherent in long cables attached to piezoelectric transducers. In addition, the impedance of the assembly is reduced from 10^{10} ohms to 10^{3} ohms. The advantages associated with FET's are reported more fully in Reference 2.

The objective of the program reported herein has been to incorporate all of the previous improvements into a skin friction transducer configuration so as to obtain performance compatible with a specific measurement problem posed by NASA/Ames. This objective has been met, and the following is a description of the transducer configuration and a report of the performance of the transducers that have been built.

SECTION II DESIGN SPECIFICATIONS

In June of 1966, Ames contacted CAL with a request for the development of a skin friction transducer to measure skin friction on a cone in the Ames shock tunnel. The previous transducer design reported by CAL showed promise of being modified to meet the requirements of the Ames experiment, and discussions between Mr. Terry of Ames and Mr. MacArthur of CAL subsequently resulted in satisfactory specifications for a new design. The specifications agreed upon are as follows:

1. The transducer must be usable for measurement of skin friction forces from .005 psi to .2 psi. It is to have less than 1% circuit noise at .005 psi and less than 1% departure from linearity up to .4 psi.

2. The ratio of skin friction sensitivity to pressure sensitivity is to be 1000 to 1 or better.

3. The transducers will not be permanently damaged by a heat transfer rate of 200 BTU/ft^2 sec applied for 30 milliseconds and the response due to this heating rate will be as small as practical considering the other specifications.

4. All design parameters will be consistent with tests lasting up to 3[illegible] milliseconds.

5. The transducer size will be less than 1/2" diameter.

6. The surface may be contoured to the surface of a cone with a radius as small as 2" at the time of manufacture but need not be easily recontoured to another surface.

7. The rise time constant $\leq$ .25 msec.

8. The response to a step [illegible] than 2% [illegible] in 50 [illegible]

9. Acceleration [illegible] indicated skin friction [illegible]

10. The allowable pressure [illegible]

SECTION II (Cont'd)

11. No permanent damage due to 30 psia overpressure.

12. The pressures across gaps at the diaphragm edge will equalize in 1 msec at any pressure from .005 to .2 psi.

13. The surface of diaphragm and exposed face of the case to match to .00025".

14. The transducer will have a solid state power amplifier, built into its case, capable of driving 150 ft. of cable that has a capacitance of 30 pf or less per foot and will satisfy the rise time specification in Item No. 7.

15. The diaphragm and entire case are to be signal ground. All high impedance circuits will be inside the metal case for protection against ionized gases and stray electric fields (such as may be produced by spark light sources).

SECTION III ADDITIONAL DESIGN CONSIDERATIONS

The program conducted in the course of the transducer development brought out three other requirements that are important for successful transducer performance. Although they had not been specifically itemized in the initial list of design requirements, careful consideration of their effect upon the transducer performance was a part of the development program. These three requirements cited below are associated with the severe environment inherent in the shock tunnel flow.

1. Experimental test programs conducted at CAL reveal that the forces experienced by skin friction and pressure transducers during the flow breakdown period following the useful part of a shock tunnel test are much larger than those felt during the steady flow portion. Therefore, it is wise to build in as much strength as practical since these transducers are to be used at rather high loads.

2. Experience has also shown that the turbulence level during the useful part of the flow varies considerably from run to run and may be high. Hence the transducers should be conservatively designed with lightly stressed elements to take advantage of the consequent greater linearity over the range of skin friction forces experienced.

3. Low sensitivity to pressure gradients in the axial or cross flow directions is essential.

SECTION IV DESCRIPTIONS OF TRANSDUCERS

Mechanical

A photograph of the complete transducer is shown in Figure 1 and a cross section drawing with the essential parts labeled is shown in Figure 2. There are two cantilever beams attached to the diaphragm by means of flexures which permit end rotation. Each beam consists of two pieces of piezoelectric ceramic material. These two halves are oppositely poled to provide first order cancellation of outputs due to tension, compression, heat, or temperature gradients (if such heating effects are symmetrically applied). The beams respond to forces in the plane of the gage surface, i.e., at right angles to the .080" dimension of the beam. One half of the beam is thus put in tension, the other in compression. The two halves are wired in series, there being no connections to the conductive surface between the halves, thus an electrical output is produced by the g_{31} piezoceramic coefficient* when the beam is bent.

A third piezoceramic element is used for acceleration compensation. It is similar to the other two but twice as wide and installed inverted for installation and wiring convenience. There is a small weight cemented to its free end, whose mass is equivalent to that of the diaphragm. This mass may be individually selected and adjusted; it is selected for best performance at sinusoidal accelerations of the transducer of ±1g at 100 cps. Experience shows that it is unrealistic to expect cancellation near the natural frequency of the transducer. There the signals may add rather than subtract at some time during the test due to very slight differences in natural frequencies between the active and the compensating beam systems. Mounting of the transducer in a model has not, as a rule, posed insurmountable problems. As noted in Section III, the device has been designed to function properly even when subjected to a considerable amount of hostile vibration. However, the specific means of attachment is important. The objective is to provide electrical insulation as

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* g_{31} coefficient defines the voltage per unit length appearing in the poled direction due to a pressure 90° to this direction as [illegible] in Technical Paper 217 published by the Clevite Corporation, [illegible], Ohio, [illegible] author.

SECTION IV (Cont'd)

well as to avoid case distortion which might impair the linearity of gage response. In addition, some vibration isolation is achieved. Figure 3 shows a mounting arrangement considered satisfactory for conditions of low to moderate model accelerations.

Description of Electronic Circuitry

The electronic amplifier is shown schematically in Figure 4 and described in detail in Reference 3. It is contained in the cavity at the bottom of the transducer case as indicated in Figure 2. The amplifier is accessible for repair by removal of the cover. Experience at CAL with this circuit over a three-year period has shown very little need for replacement of any of the parts. Protection from humidity, ionization or corrosive gases is provided by epoxy cement over most components and connections and by liquid R. T. V. on the FET. There is a 40 kohm resistor in series with the amplifier output to protect it from the necessity of driving the reactive load of the cable. This limits the frequency response and produces a 4% loss when used with a 1 megohm load. This loss is automatically taken care of if both calibration equipment and shock tunnel recording equipment have the same input impedance.

SECTION V DISCUSSION

The piezoelectric beams are designed for maximum strength within the space allotted. The beam will withstand 2 psi with a factor of safety of 15. This implies a high stiffness with a resulting high natural frequency of the system (>12,000 cps). The high natural frequency is desirable as it reduces the chances of excitation either by a step air load or mechanical loads in the model. It also facilitates filtering out the natural frequency from the electrical signal. The upper limit of allowable beam strength or stiffness is that determined by the need for sufficient charge from displacement by the piezoelectric beams to supply gate circuit losses with less than 2% droop in 30 milliseconds. The acceptable limit of minimum signal is determined by the desired signal to noise ratio. Since the circuit noise is more consistent than the peak overloading of the beam due to dynamic airloads or excitation of the mechanical system natural frequency, the design is established at a low signal level, close to the minimum acceptable signal to noise ratio. The signal to noise ratio is 200 to 1 for a pass band of .1 to 3,000 cps at a skin friction level of .005 psi. Because of the high beam strength, the linear range of the transducer is considerably in excess of the design requirements. This is shown in Figure 5.

Epoxy cement is used to attach the diaphragm to the flexures and the flexures to the beams (Figure 2). This choice was made to obtain an attachment strength commensurate with the strength of the rest of the system rather than using another attachment material which would allow the diaphragms to be removed more easily. It is entirely possible to recontour the diaphragms to some extent without separating them from the beams. Removal of the diaphragms is possible by the use of heat.

A rather thick (.010") diaphragm of low temperature coefficient material (invar) was chosen for thermal protection of the piezoceramic beams. The choice of invar reduces to a minimum the diaphragm distortion due to uneven heating thereby, in turn, minimizing the induced loads in the two [illegible] beams. As shown in Figure 6, sufficient thermal lag is provided by the thin diaphragm and flexures to keep temperature induced signals from the [illegible]

SECTION V (Cont'd)

within the design limits. The stiffness of the thick diaphragm is advantageous in that it is more easily contoured and also resists distortion due to pressure loads. Larger acceleration loads associated with the higher mass of the invar over that of a magnesium diaphragm are readily accommodated in the design of the transducer.

Calibration Apparatus

A photograph of the apparatus for applying a shear load step is shown in Figure 7. A skin friction transducer is mounted near the center of a flat aluminum disc 16" in diameter and 1/2" thick. The disc has a hole at the center through which a very thin thread passes, by means of which a weight may be attached to the diaphragm of the transducer. The weights are a series of steel ball bearings 1/8" to 1" in diameter. After letting the system settle, the weight is suddenly raised by tilting the center pivoted beam shown at the bottom of the picture to remove the shear load from the transducer. When the right-hand side of the beam is thrust sharply downward, a microswitch is operated a few milliseconds before beam contact is made to the suspended ball bearing. The switch is used to initiate the sweep of the oscilloscope, producing a trace as shown in Figure 8. A block diagram of this apparatus is shown in Figure 9 in which an additional feature to provide a readability of .1% is shown. This feature, a null circuit, introduces a precise adjustable voltage into the B channel of the differential input oscilloscope at the moment of data rise thereby permitting the use of much more amplification in the oscilloscope. Typically 1 cm of height on the oscilloscope is made to be 1% of the full signal. By this means a close examination may be made of imperfections of the beams, or the entire transducers, that effect its time response.

Calibration Procedures

The sequence of skin friction calibration and measurement of response to pressure, heat and acceleration is [illegible] arbitrary. [illegible] of the [illegible] tests and those that may show the transducer unsatisfactory [illegible]

SECTION V (Cont'd)

performed first in order to save time; also, severe tests are performed early in order to save calibration time should the unit be damaged. CAL has adopted the procedure, therefore, of checking first exposure to heat, then acceleration sensitivity (adjusting the compensating weight if necessary) and third, the pressure sensitivity is measured. A pressure check is accomplished by suddenly venting a pressure of 1 psi above atmospheric to the transducer by means of a solenoid operated valve. This is the same manner that pressure transducers are calibrated. The step produced has a rise time of about 1 millisecond so it is not an adequate method for checking the flow rate around the diaphragm; this flow varies with shock tunnel conditions and is under the control of the user. The transducers do not have a nonmetric ring around the diaphragm, thus giving the user flexibility in control of the edge gap. Caps are provided to protect the diaphragms during storage.

Calibration for skin friction sensitivity is accomplished using the apparatus shown in Figure 7 and the block diagram of Figure 9 as previously described. The mounting disc is suspended from a beam near the ceiling on long, soft rubber cords so that building vibrations do not appear in the records. Previous attempts to use a 2" thick steel surface plate with 2" thick rubber vibration damping pads proved inadequate even though there were no sources of vibration within 50 ft. of the calibration area. The calibration procedure consists of a sequential loading of weights starting with the smallest up to the maximum which is equivalent to 2.7 psi. The value of maximum load exceeds the design requirement and is chosen to determine linearity of the system at as high a load as possible because of the importance of linearity in the case of high dynamic components of loading during testing.

<u>Bench Data</u>

A tabulation of the essential properties of the six skin friction gages is shown in Table I. Serial numbers of the units delivered do not start with 1 because those prototypes with inferior characteristics and those damaged during tests are not included. All transducers were given numbers prior to

SECTION V (Cont'd)

assembly to avoid subjection of the finished transducer to the consequent severe acceleration of engraving.

Shock Tunnel Data

Four of the six transducers were subjected to a series of shock tunnel runs. For these tests, two of them had additional FET circuits without the 40 kohm series resistors to allow monitoring of the high frequencies present. Figure 10 shows the filtered skin friction time record. Figure 11 shows the actual forces seen by the measuring beams during the same run as Figure 10. It is to be noted that good records are obtained in spite of the large peak signals at high frequency. The validity of the record was established by a repeat run with the gages covered and during which no skin friction was indicated.

Conclusions

Six skin friction gages suitable for use in the Ames Shock Tunnel have been constructed and delivered to Ames. They are of an advanced design with characteristics superior to previous existing CAL skin friction transducers. The specifications requested by the sponsor have been met. This report has described the gages, the procedures necessary for their use and individual transducer characteristics.

SECTION VI

REFERENCES

1. MacArthur, R. C.: "Transducer for Direct Measurement of Skin Friction in the Hypersonic Shock Tunnel," CAL Report No. 129, August 1963.

2. Wallace, J. E., McLaughlin, E. J.: "Experimental Investigations of Hypersonic, Turbulent Flow and Laminar, Leeward-Side Flow on Flat Plates," Technical Report AFFDL-TR-66-63, Vol. 2, July 1966.

3. MacArthur, R. C. and Martin, J. F.: "Use of Field Effect Transistors in Shock Tunnel Instrumentation Circuits," Paper presented at IEEE Second International Congress on Instrumentation in Aerospace Simulation Facilities, Stanford University, August 1966.

4. Wilkinson, D. B.: "Development of a Flush Diaphragm Piezoelectric Pressure Transducer, CAL Report No. AN-1832-Y-2, February 1964.

TABLE I

Transducer Number	2	3	4	6	14	15
Diaphragm Contour 5° Half Angle Cone Station (ft.)	2.5	5.5	8.0	8.0	9.5	9.5
Sensitivity to Skin Friction (mv/psi)	1463	968	1116	1020	1465	1529
Sensitivity to Pressure (mv/psi)	.4	.16	.5	.2	1.0	.8
Resonant Frequency (cps)	21,000	14,000	17,000	15,900	18,000	12,900
Sensitivity to Acceleration in Skin Friction Direction (mv/g)	.7	.5	.1	1.0	.1	.2
Response to 35 BTU/ft^2-sec (mv)	6.	6.	6.	5.	1.	5.

NOT REPRODUCIBLE

Figure i PHOTOGRAPH OF COMPLETE TRANSDUCER

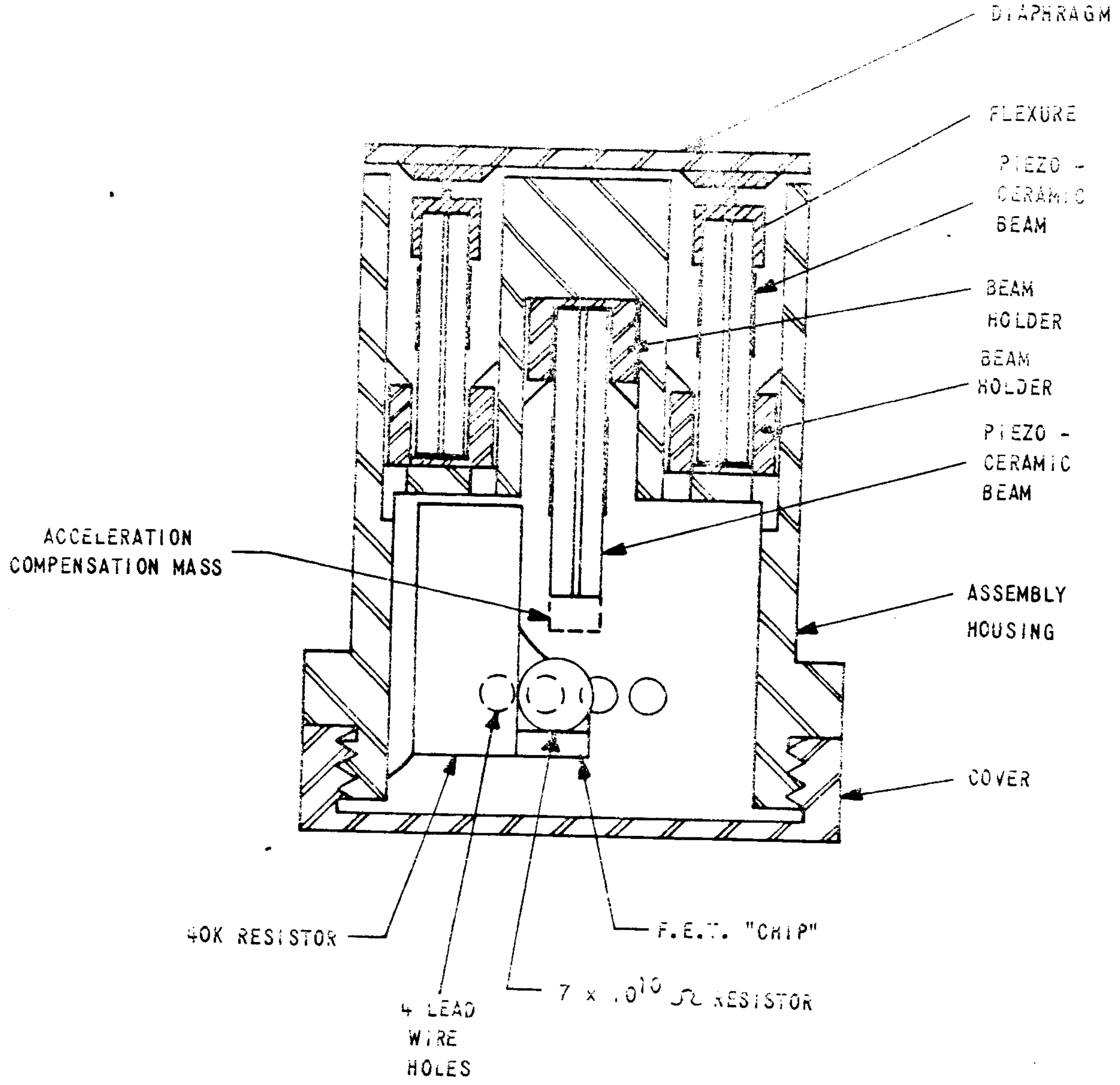

Figure 2 DRAWING OF SECTION THROUGH TRANSDUCER

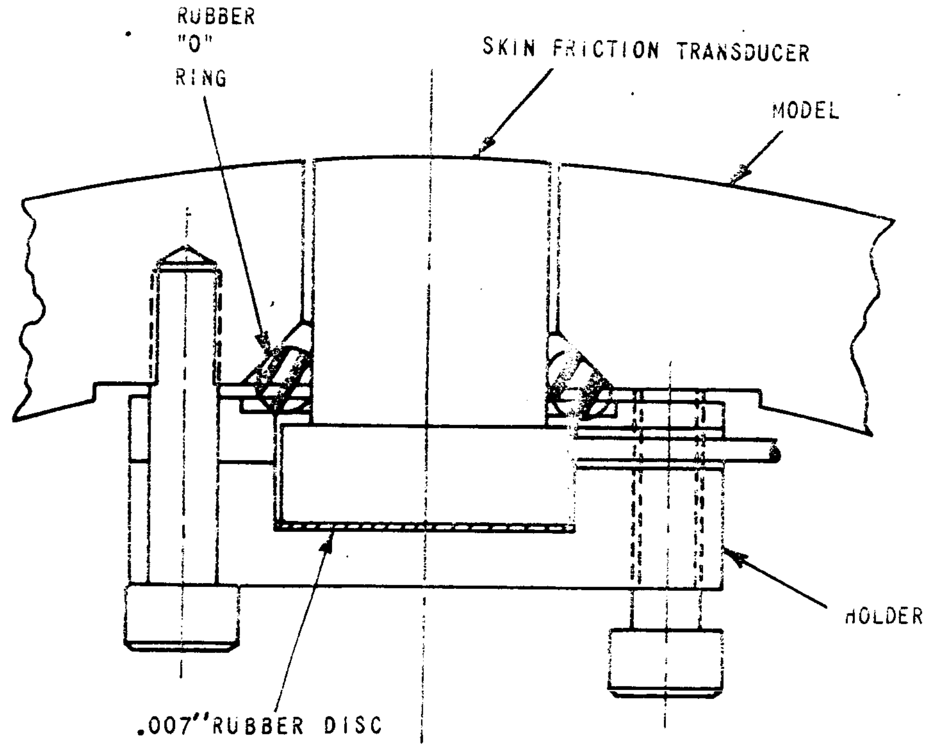

Figure 3 DRAWING OF HOLDER FOR MOUNTING TRANSDUCER IN MODEL

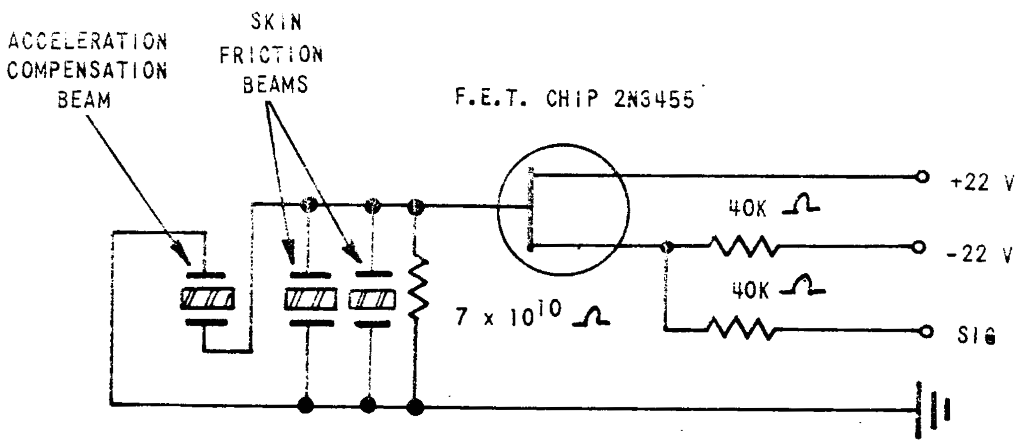

Figure 4 SCHEMATIC DIAGRAM OF ELECTRONIC CIRCUIT

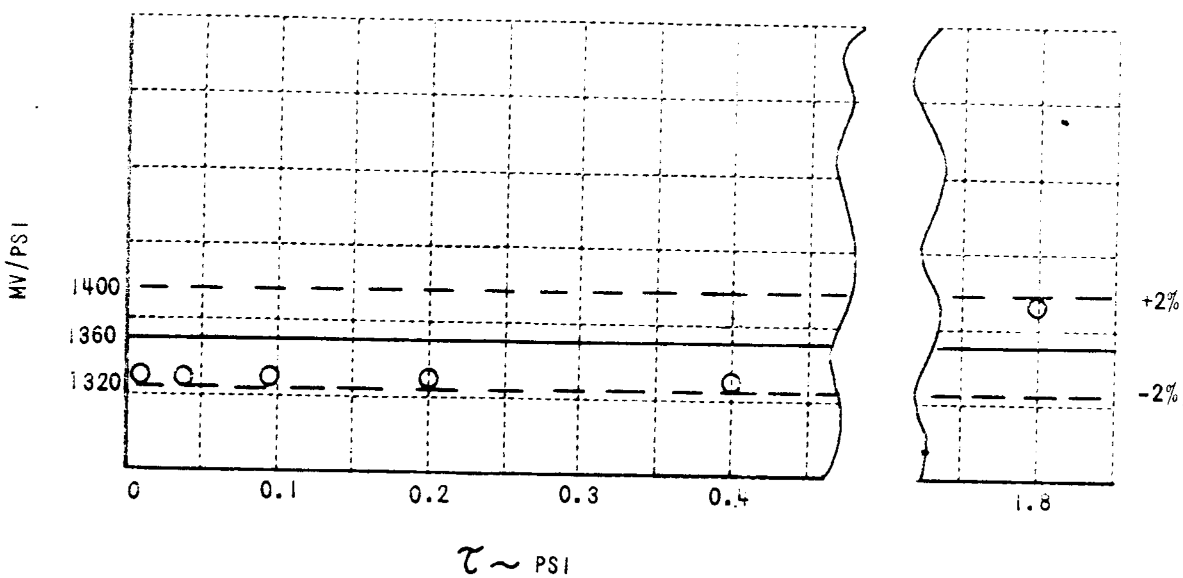

Figure 5 GRAPH OF LOAD vs. SENSITIVITY

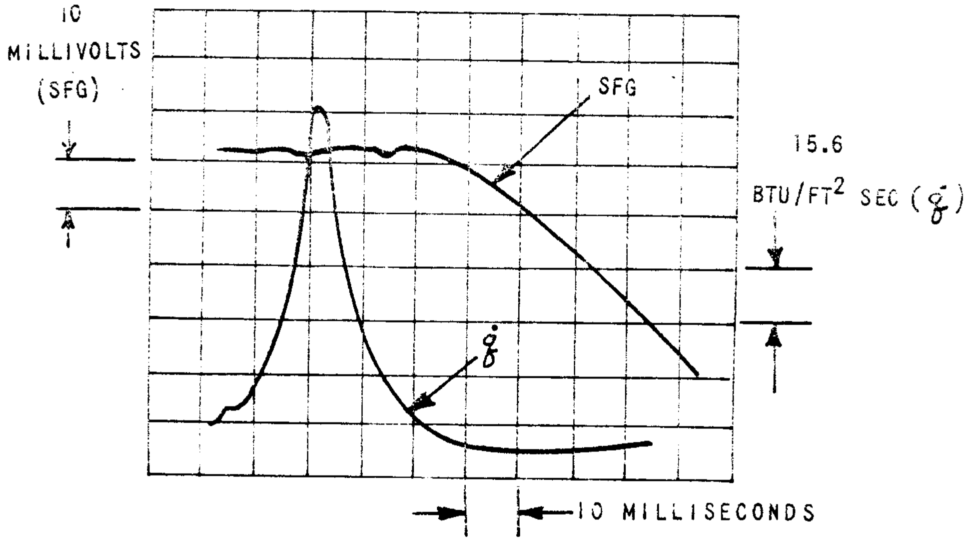

Figure 6 OSCILLOSCOPE RECORD OF RESPONSE TO HEAT

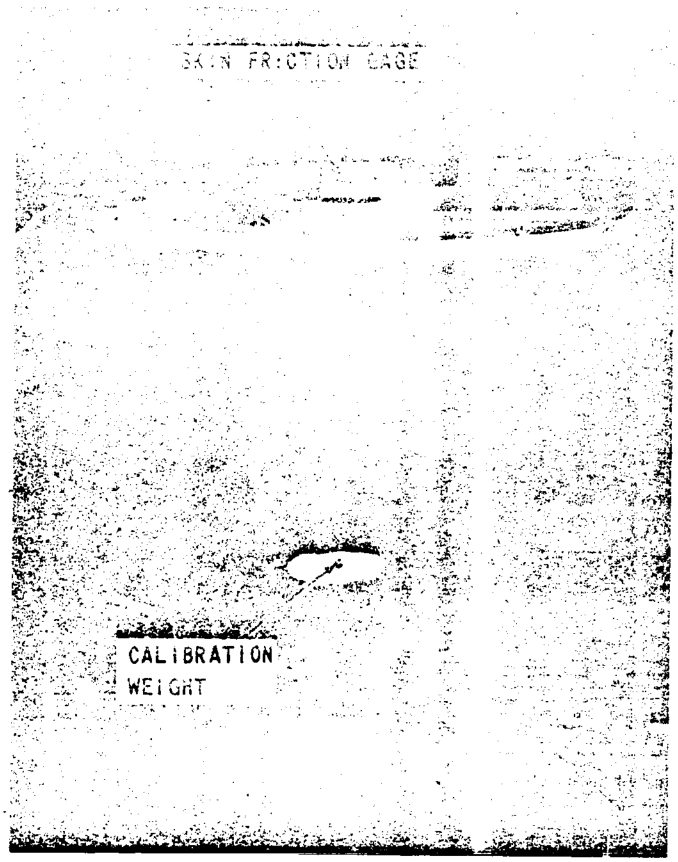

Figure 7 PHOTOGRAPH OF SHEAR FORCE LOADING FIXTURE

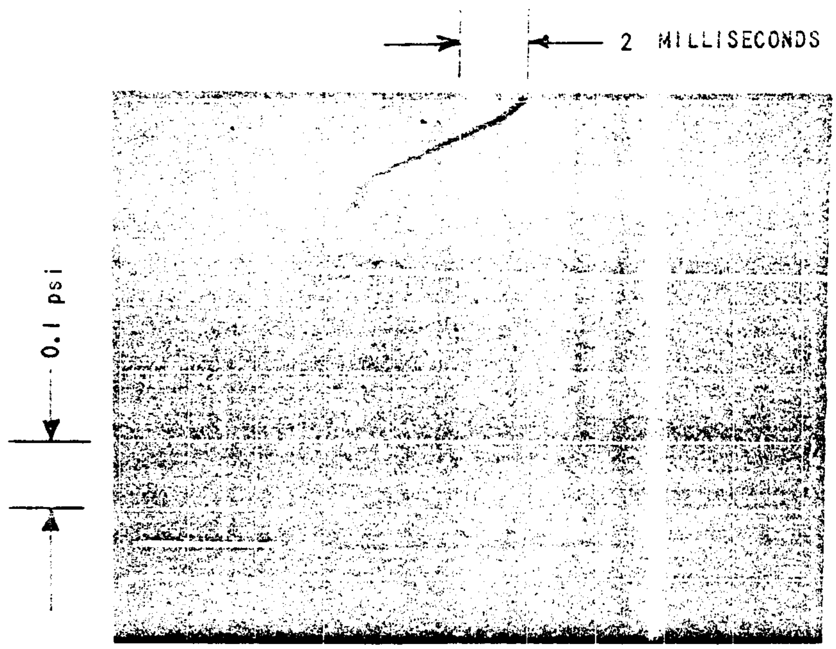

Figure 8 OSCILLOSCOPE RECORD OF TIME RESPONSE TO STEP OF SHEAR FORCE

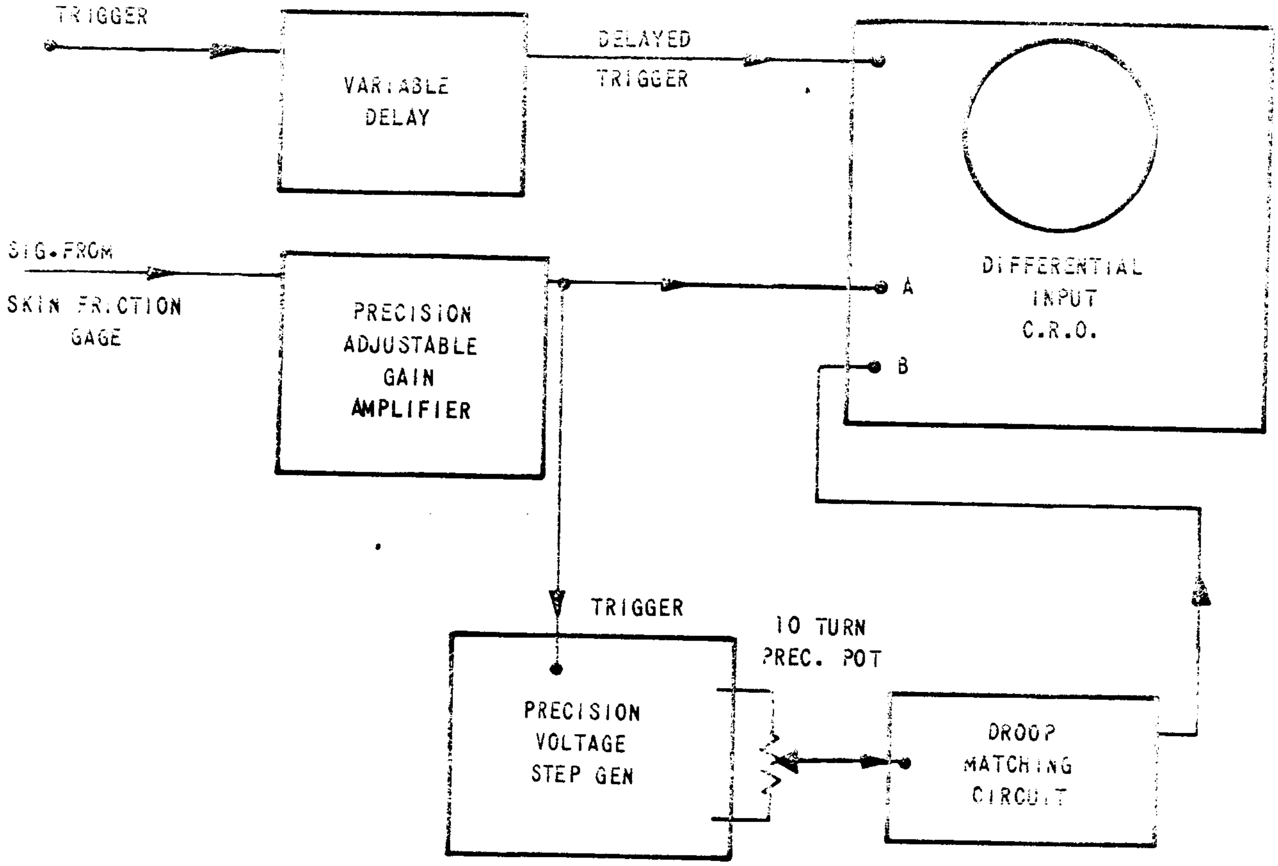

Figure 9 BLOCK DIAGRAM OF CALIBRATOR

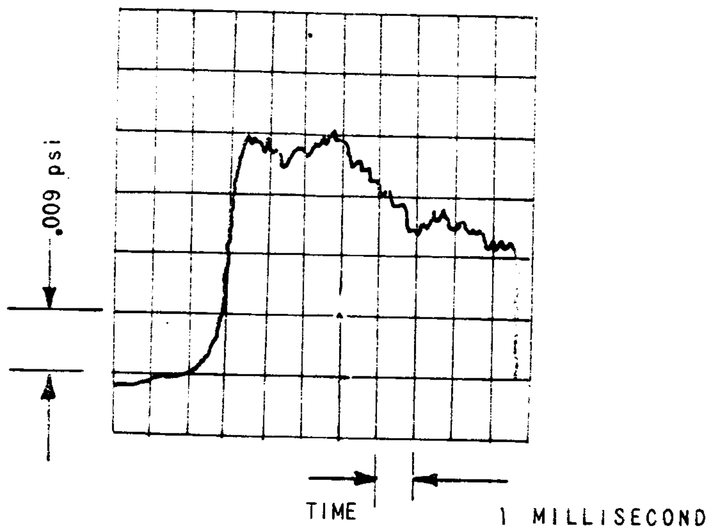

Figure 10 SKIN FRICTION RECORD DURING TEST IN THE SHOCK TUNNEL

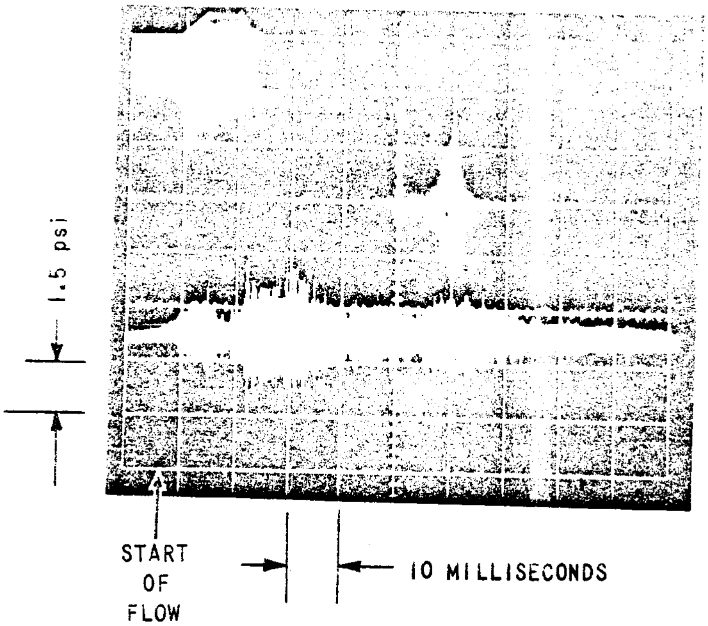

Figure 11 SHOCK TUNNEL RECORD SHOWING LARGE SKIN FRICTION FORCES DURING FLOW BREAKDOWN